AUTOMATIC DETECTION ALGORITHM OF INTRACRANIAL PRESSURE WAVEFORM COMPONENTS

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Abstract— **We describe an automated detection algorithm that may be used to identify the percussion peak (P), tidal peak (T), dichrotic notch (N), and dichrotic peak (D) components of the intracranial pressure (ICP) signal. The algorithm uses a moving average filter to remove quantization error, a lowpass filter to identify the beat series, and a local search to identify the components of each beat. The algorithm was compared with two experts' visual identification of the percussion components of 997 beats recorded from three subjects. The algorithm accuracy rate was 99.3% with an acceptance interval of 8 ms (± 1 sample).**

Keywords— **Physiologic Beat Detection, Intracranial pressure**

I. INTRODUCTION

Traumatic brain injury (TBI) remains a significant cause of mortality and morbidity in both children and adults [1]. Severe TBI often leads to increased intracranial pressure (ICP) that may result in worsening brain injury and outcome. Current methods of ICP signal analysis are based on time- or frequency-domain metrics such as mean, standard deviation, peak amplitude, histograms, and power spectral density [2]. Few investigators have analyzed variations in the morphology of the ICP signal because they lack detection algorithms that can automatically identify each of the beat components.

There is a periodic beat in the ICP signal that corresponds with each heart beat and pulse in arterial blood pressure. Each beat in the ICP signal is composed of four components: a percussion peak(P), a tidal peak(T), a dichrotic notch (N), and a dichrotic peak (D). Fig. 1 shows an example of these four components identified in an ICP signal. An accurate and automated extraction algorithm would enable investigators to characterize the shape of the ICP signal, including the beat-to-beat interval data and the relative changes in amplitude between peaks. Fig. 2 shows an example of some of the signal metrics that could be used to characterize the signal components. We describe a fully automatic ICP beat detection algorithm that locates each PTND component.

II. METHODOLOGY

A. ICP Monitoring and Data Acquisition

For this study, we detected the beat components in subjects with severe traumatic brain injuries from the Pediatric Intensive Care Unit, Doernbecher Children's Hospital. This study was reviewed and approved by the Institutional Review Board of Oregon Health and Science University, and the requirement for informed consent was waived. ICP was monitored continuously using either a ventricular catheter or parenchymal fiber-optic pressure transducer
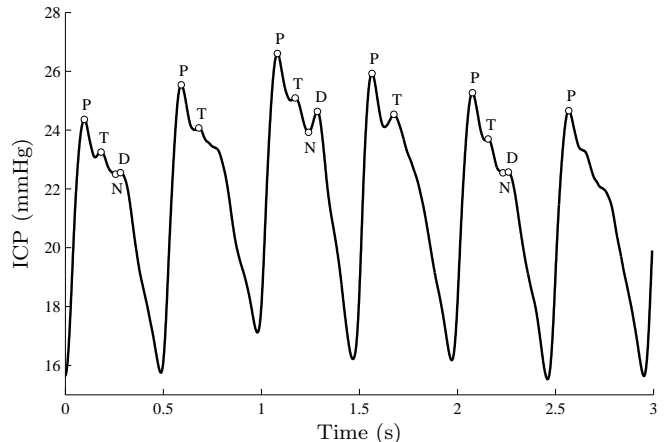

Fig. 1. Example of the PTND components of an ICP signal versus time as labeled by an expert. Not all of the components can be clearly identified for each beat. Note that only the percussion (P) component can be identified in the last beat.
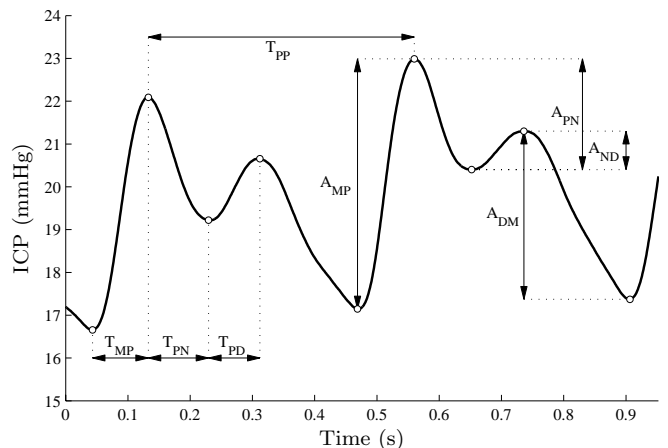

Fig. 2. Plot of the intracranial pressure versus time during two heart beats. This figure also illustrates the signal metrics that can be used for further studies once the PTND components are detected for each beat. These metrics include the intervals and relative amplitudes of each pair of the PTND components. In this example, the tidal peak is absent.

(Integra NeuroCare, Integra LifeSciences, Plainsboro, NJ). The ICP monitor was connected to an Agilent Merlin patient monitor (Agilent, Palo Alto, CA) which sampled the ICP signals at 125 Hz. An HPUX workstation automatically acquired these signals through a serial data network, and they were stored in files containing six-hour epochs on CD-ROM [3].

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Abstract

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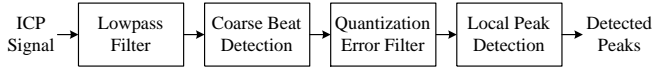| Classification of Abstract	Limitation of Abstract
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Fig. 3. Block diagram of the automatic detection algorithm showing each of the four stages.
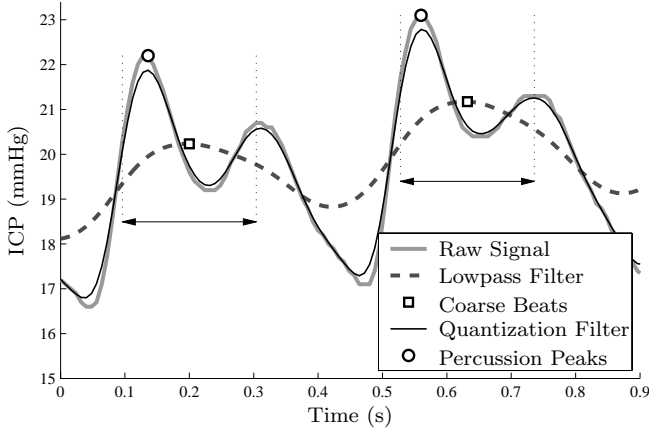

Fig. 4. Example of how the different stages of the detection algorithm locate the percussion peaks in the ICP signal. The dichrotic peak in the second beat cannot be precisely located in the raw signal due to quantization error, but it can be accurately identified after smoothing with the moving average filter.

B. Detector Description

The PNTD detector is divided into four stages, as shown in Fig. 3. The following sections describes each of these stages in detail.

B.1 Stage 1: Lowpass Filter

Before the algorithm identifies each component of the PTND complex, it first coarsely locates each heart beat. To simplify this task, the signal is filtered with a moving average filter. This reduces the effect of high-frequency noise due to patient movement and other external sources. The moving average is calculated using 30 samples (0.25 s) and the signal is filtered forward and backward to eliminate phase shift. This stage ensures that the filtered signal is shaped roughly like a sinusoid with one cycle per beat. Fig. 4 shows an example of the signal after this stage of lowpass filtering.

B.2 Stage 2: Coarse Beat Detection

The lowpass filtered signal from the previous stage contains exactly one peak per heart beat, except in regions that contain artifact. This stage estimates the location of each heart beat at the location of the peaks in the filtered signal from the previous stage. Fig. 4 shows an example of two beats coarsely located using this method.

B.3 Stage 3: Quantization Error Filter

Although high-precision analog-to-digital (AD) converters are commercially available, most commercial patient monitors use relatively low precision ($\approx$ 8 bits) because the signals are primarily used to display the time aver-

TABLE I

NUMBER OF MOVING AVERAGE FILTER TAPS (LENGTH) FOR VARIOUS RATES OF QUANTIZATION ERROR, AS SPECIFIED BY RQE.

RQE	Taps
0.00–0.07	2
0.07–0.25	5
0.25–0.50	10
0.50–0.75	20
0.75–1.00	25

aged mean ($\approx$ 5 s) and trends on the bedside monitor. In monitoring the ICP signal, the low-resolution problem is exacerbated by the large amplitude range, approximately -5 to 100 mmHg, compared to the typical peak-to-peak amplitude range 4 mmHg. To partially compensate for quantization error, this stage smooths the signal with a moving average filter.

The amount of quantization error varies between subjects and among ICP monitors. To estimate the degree of quantization error, this stage calculates the *relative quantization error* (RQE), which is defined as the number of consecutive samples that are equal to each other divided by the total number of samples. Table I shows the length of the moving average window used for various ranges of RQE. Fig. 4 shows an example of a signal with quantization error before and after filtering.

B.4 Stage 4: Local Peak Detection

The final stage of the algorithm searches for the PTND components in the signal after quantization error filtering. Specifically, the algorithm searches from 0.24 s prior to 0.24 s after each coarse beat temporal location for each PTND component. Since the lowpass filtered signal used to locate the coarse beats is in phase with the PTND complex, the PTND components are detected in order, from left to right. This stage only searches for three peaks and one notch per coarsely detected beat.

C. Expert Validation

Two experts, CC and SL, visually identified the time of each percussion component in ICP signals recorded from three different patients. Each segment was 2.67 min (20,001 samples) in duration. The segments were screened for significant artifact. The experts used custom software written in MATLAB®(MathWorks, Natick, MA) to visually identify and record each percussion peak. The tool enabled the experts to display the interbeat intervals to find regions where beats were potentially mislabeled. In regions of uncertainty, the experts selected peaks that minimized interbeat interval variability.

III. RESULTS

The percentage accuracy of the algorithm was calculated by the equation $\frac{\text{NB} - \text{FD}}{\text{NB}}$, where NB is the total number of beats detected by the expert and the number of false detects (FD) is the sum of the false negatives (FN) and

TABLE II

RESULTS FOR VARIOUS ACCEPTANCE INTERVALS.

Interval (ms)	8.0	24.0	48.0	120.0
DT–CC	99.40	99.40	99.60	99.80
DT–SL	99.30	99.30	99.30	99.70
CC–SL	99.70	99.70	99.70	99.90

TABLE III

RESULTS FOR ACCEPTANCE INTERVALS (AI) OF 8.0 MS AND 96 MS. NB DENOTES THE NUMBER OF BEATS DETECTED BY THE EXPERT. FP, FALSE POSITIVES; FN, FALSE NEGATIVES; FD, FALSE DETECTS.

	AI	NB	FP	FN	FD	Accuracy
DT–CC	8 ms	997	3	3	6	99.40%
DT–SL	8 ms	996	4	3	7	99.30%
CC–SL	8 ms	997	1	2	3	99.70%
DT–CC	96 ms	997	1	1	2	99.80%
DT–SL	96 ms	996	2	1	3	99.70%
CC–SL	96 ms	997	0	1	1	99.90%

false positives (FP): FD = FN + FP. A beat identified by an expert was counted as a false negative if the algorithm did not also identify a beat within a specified acceptance interval. A beat identified by the algorithm was counted as a false positive if the expert did not also identify a beat within the same acceptance interval.

The detection algorithm was 99.40% accurate with an acceptance interval of 8 ms (±1 sample) compared with expert CC, and 99.30% accurate compared with expert SL. The expert SL was 99.70% accurate compared with CC. Table II shows the accuracy of the algorithm and the experts for four different acceptance intervals. Fig. 5 shows the accuracy for acceptance intervals ranging from 8 ms to 200 ms. Table III demonstrates how the accuracy was calculated for acceptance intervals of 8 ms and 96 ms. Figs. 6 and 7 show examples of the percussion peaks identified by the detection algorithm and the two experts over 15 s segments of two ICP signals with different morphology.
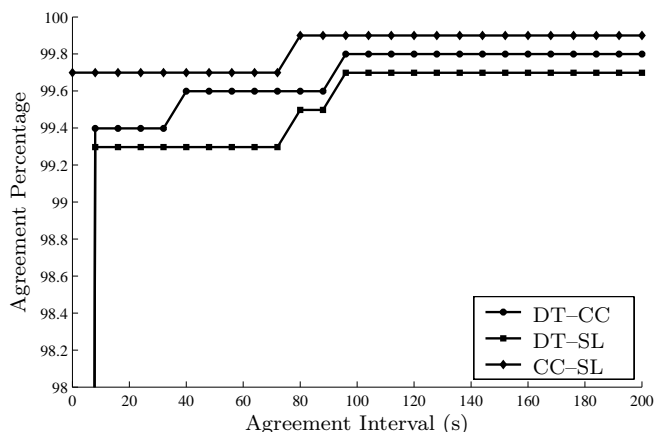

Fig. 5. Percent accuracy versus acceptance interval for the detection algorithm (DT) and the two experts.
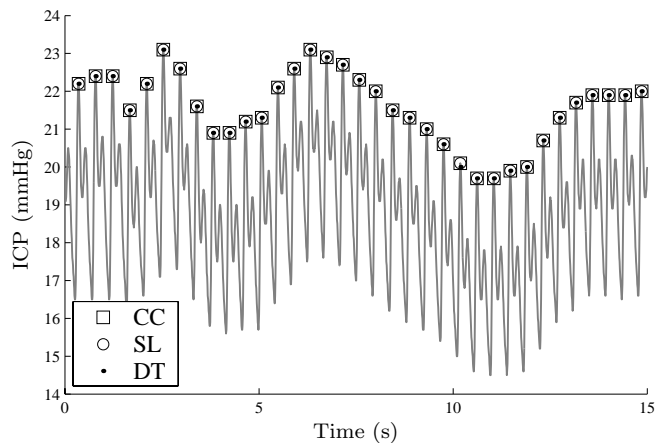

Fig. 6. Example of the percussion peaks identified by the two experts and the detection algorithm (DT).
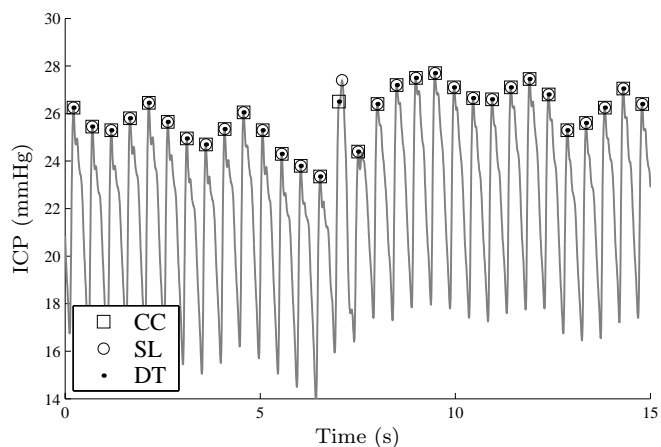

Fig. 7. A second example of the percussion peaks identified by the two experts and the detection algorithm (DT). Note that the signal morphology is different than Fig. 6.

IV. DISCUSSION

The results show that the algorithm is nearly as accurate as the experts are with one-another and may therefore be used as an automated method for beat detection and analysis. The potential applications for this algorithm lie in further research studies that more closely analyze the ICP waveform and its components during traumatic brain injury (TBI) and in other disease states that affect ICP. Additionally, more accurate real-time monitoring of the ICP signal may be possible.

The key advantage of using an automatic algorithm for beat detection is the gain in efficiency. The experts took one hour to identify almost 1,000 beats in the ICP signals spanning a total period of approximately eight minutes. The algorithm required approximately 1.5 s.

We also briefly investigated segments with significant artifact due to patient movement and clinical events, such as the one shown in Fig. 8. These segments are screened from signal analysis because the peaks cannot be reliably identified by an expert. Preliminary results indicate that the algorithm is nearly as consistent as two experts at identifying the percussion component in regions with signifi-
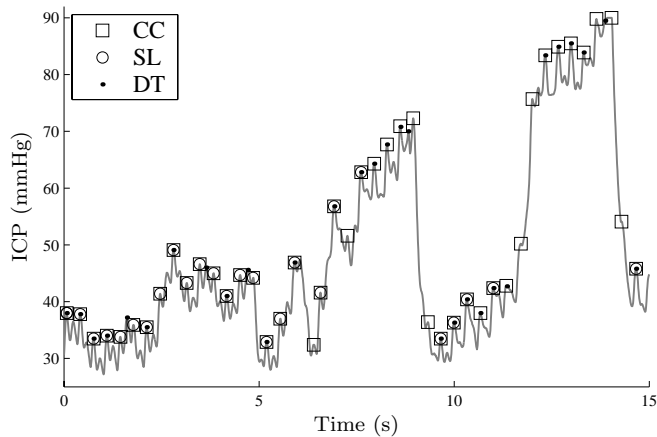
Fig. 8. Example of how consistent the two experts, CC and SL, were as compared with the detection algorithm, DT, on a segment with significant artifact.

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cant artifact. We are currently investigating the use of other physiologic signals, such as arterial blood pressure and electrocardiogram, to identify the temporal location of ICP components in regions with significant artifact.

With the exception of one of the eleven subjects available for ICP analysis, the waveforms were classified as low pressure waves (i.e. high brain compliance) where the percussion (P) component is the highest and most easily identified (see Fig. 1). For this type of low pressure ICP signal, the algorithm and the experts could only clearly identify two peaks. In this case, we could not determine whether the second peak was the tidal or dichrotic component. In subjects with low brain compliance, the three components were present and easily identifiable. In this situation, the tidal component is the peak with the highest amplitude.

V. Conclusion

This paper describes an automatic ICP detection algorithm that locates each of the PTND signal components. The algorithm is composed of four stages: a lowpass filter, a coarse beat detector, a quantization error filter, and a local peak detector. The results show that the algorithm achieved an accuracy of no less than 99.3% compared to two experts with an acceptance interval of 8 ms ($\pm$ 1 sample).

This detection algorithm may be used to analyze ICP signals on a beat-to-beat basis rather than using coarse estimates of the ICP signal properties such as mean and standard deviation. Having the percussion-to-percussion interbeat information, the peak-to-valley amplitudes, such as percussion-to-dichrotic notch, and percussion slopes may enable researchers to more precisely analyze the ICP signal properties.

VI. Acknowledgments